b. Dickinson-Schuske Generalized Area of Intersection Model[26]

A more useful method of calculating the interaction effect of intersecting piping was recently proposed by Dickinson and Schuske. This method, entitled "The Generalized Area of Intersection" (GAI) method, is based upon experimental[27] data and calculational correlation with intersecting piping experiments carried out by the Rocky Flats Division of The Dow Chemical Company. The material for this model has been abstracted from the referenced article. The GAI model calculates both simple and complex intersections providing different limits on the intersection area and column size depending on the number of quadrants that contain arms. Although the experiments were carried out with enriched (93.1 wt% ^{235}U) uranyl nitrate, the results are **conservative** for plutonium nitrate solutions in the range of approximately 50 g/l to ≈ 650 g/l depending upon the ^{240}Pu content. (See page II.B.1-14).

Definitions

Diameter - Always the inner diameter of a pipe.

(Central) Column - The main column or pipe from which branching of arms occurs; the largest diameter pipe.

Arm - Any pipe or cylinder intersecting the central column.

Intersection Area - The area of intersection of an arm with the tangent plane of the column at the point where the axis of the arm intersects the column. (See Figure 1, where D = diameter, theta (Θ) = angle between arm axis and column axis, and A = area of intersection).

Sector - Any 18-inch length of the central column. (See Figure 2).

Quadrant - One-fourth of a sector; the sector is divided into four quadrants by two perpendicular planes intersecting along the axis of the sector. (See Figure 2).

Minimal Reflection - The reflection from the ∿ 1/8-inch-thick steel walls of the pipes only.

Nominal Reflection - Reflection from 1/8-inch-thick steel walls of the pipe plus 1/2-inch of water reflector (or an equivalent amount of reflection) around the pipes.

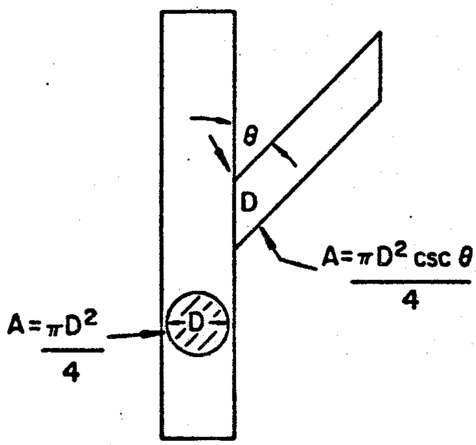

Fig. 1. Surface area in contact with central column.

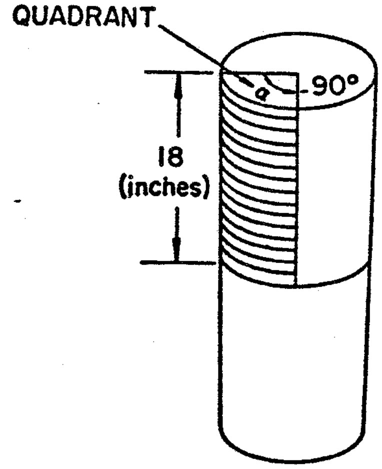

Fig. 2. Sector and quadrant definitions.

Full Reflection - Reflection due to full water flooding of a pipe system (pipes have 1/8-inch-thick steel walls); safe dimensions are calculated by reducing all diameters in the minimal cases by a factor of 0.635.(27)

Since the experimental information was limited and since the 05R code(28) had shown acceptable accuracy in reproducing experimental results, the 05R code was used to generate the necessary critical data. Later, calculations were performed to verify that the safe dimension pipe systems actually were far subcritical ($k_{eff} + 4\sigma < 0.95$).

The procedure used to derive the safe dimensions of the GAI model is to first select arbitrarily a reasonable central column diameter and then to calculate critical arm diameters for the case of minimal reflection for the following configurations: (a) the simple repeating T (one quadrant per sector), and (b) two quadrants per sector. The cases for 3 and 4 quadrants per sector are combined and are handled as presented in reference 27. Safe dimensions were obtained from these critical cases by reducing the central column diameter and the arm diameters by 10 to 15 percent. The safe dimensions for nominally and fully reflected systems were obtained by applying a reflector savings correction to the data for minimally reflected systems.(27)

All previous models had been limited to the case of a single central column, leaving it up to the user to decide when a second column was sufficiently far away to be considered isolated. No experimental results exist for the case of interconnected pipe systems, each consisting of a central column with attached arms. However, data on the interaction of cylinders (i.e., columns) indicate that interaction decreases rapidly with distance between cylinders. Since the increase in k_{eff} due to a second column at a separation of two feet was less than one standard error, the two-feet distance was selected as the minimum separation permitted by the GAI model. Because of the smallness of the change produced by adding a second column, it is inferred that a third column would also produce an acceptably small change in k_{eff}, although no calculations were done to study the effect of a third column. An example (see Example 2) is presented of a system containing three interconnected columns, and an 05R calculation verified that the diameters and separations calculated by the GAI model are safe.

Rules Defining the GAI Model

1. The area of intersection of the arms with the column must be calculated for all quadrants containing arms, and the calculated area must not exceed the maximum value given in Table II for the appropriate number of quadrants used and reflection condition. The intersection area must be distributed in such a way that it is impossible to find any quadrant which contains more area than that permitted by Table II.

2. The central column diameter must not be greater than the appropriate limiting value given in Table II.

3. A maximum of three columns is permitted, and the center-to-center distance between any pair of columns must be at least two feet.

4. For the case of nominal or full reflection, a maximum of four arms per quadrant is permitted. There is no limitation on the number of arms per quadrant in the case of minimal reflection.

Examples

The following examples illustrate the application of the GAI model. In each case, the goal is to maximize pipe diameters and minimize spacings. All pipes are assumed to be filled with enriched (93.1% by weight ^{235}U) uranyl nitrate solution at a concentration of 450 g/liter of uranium, and minimal reflection is assumed.

TABLE II

Maximum Intersection Areas and Column Diameters Permitted by the GAI Model

	Minimal Reflection		Nominal Reflection		Full Reflection	
Number of Quadrants Containing Arms in a Sector	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (sq. in.)	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (sq. in.)	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (sq. in.)
1	7.25	41.28	6.25	30.68	4.60	16.62
2	7.00	29.70	6.00	20.83	4.44	11.98
3 or 4	6.50	23.75	5.50	16.00	4.12	9.60

Example 1 (See Figure 3)

Note that arms 1-6, all of diameter d_2 must be placed in the same sector. Assume that the separation, S, is large enough to put arms 7-10, all of diameter d_3, in a separate sector. For the first sector (arms 1-6), only two quadrants contain arms, and hence each quadrant is permitted 29.7 square inches of intersection area, giving

$$d_2 = \sqrt{\frac{4}{\pi}\left(\frac{29.7}{3}\right)} = 3.55 \text{ inches}$$

For the sector containing arms 7-10, the four quadrants are used, and hence d_1, the column diameter, is 6.5 inches, and d_3 = 5.5 inches.

Finally, the separation, S, must be chosen large enough so that no quadrant contains more intersection area than permitted by Table II. This is accomplished by setting S = 18 inches - 3.55 inches = 14.45 inches.

By comparison, the maximum arm diameters permitted by the GEC model (see page V.B.1-9 - section on comparison of GEC and GAI) for a 6.5-inch column are d_2 = 3.72 inches and d_3 = 5.02 inches.

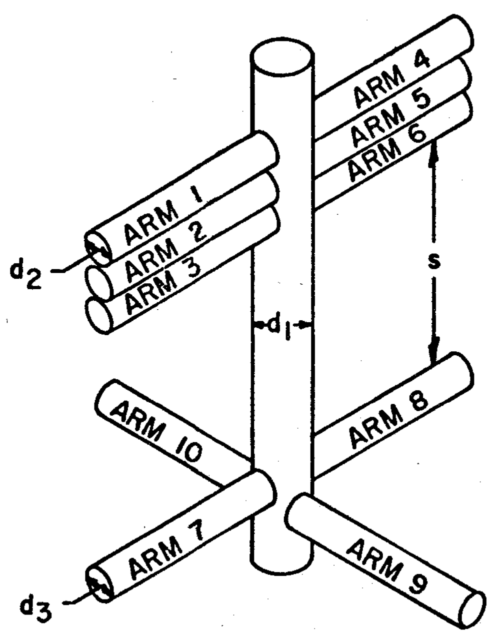

Fig. 3. Geometry for Example 1.

Example 2 (See Figure 4)

Consider first the spacing of the columns, since that is independent of arm or column diameters. The distances S_1 and S_2 must each be 24 inches; then the distance between columns 1 and 3 is $24\sqrt{2}$ inches.

For column 1, there is only one sector to consider, and it has two quadrants containing arms. Therefore, column 1 may have a diameter of 7.0 inches, and each quadrant may contain 29.7 square inches of intersection area; thus, arm 2 may have a diameter of 6.15 inches and arm 1, which is at 45 degrees, a diameter of 5.17 inches. Note that the diameter of arm 2, which also intersects column 2, may have to be reduced to make column 2 safe.

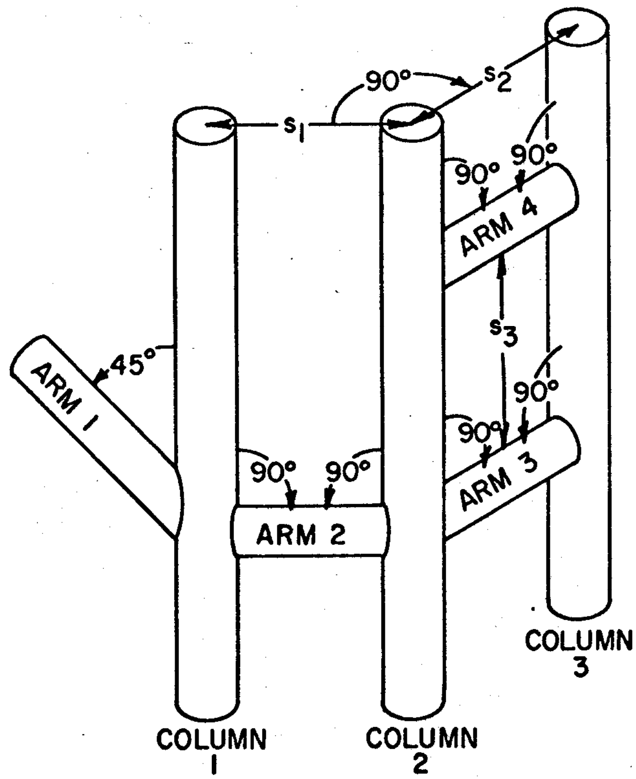

Fig. 4. Intersecting system with three columns. Permissible pipe diameters are calculated in Example 2.

Regarding column 2, assume that the distance S_3 will be chosen so that arms 3 and 4 are in different sectors. Then the sector containing arm 4 uses only one quadrant. However, the sector containing arms 2 and 3 has two quadrants containing arms, and hence column 2 is limited to a diameter of 7 inches. Arms 2 and 3 may each be 6.15 inches in diameter (so the previously assigned diameter for arm 2, relative to column 1, is allowed to stand). Arm 4, which is permitted

41.28 square inches of intersection area (corresponding to a diameter of 7.25 inches), can be only 7 inches in diameter, since the arm diameter cannot be larger than the column diameter.

Finally, column 3 has two sectors to consider, each of which contains only one arm. Hence, column 3 may have a diameter of 7.25 inches. Arms 3 and 4 are also permitted 7.25-inch diameter, so the smaller diameters already assigned also satisfy the safety criteria for column 3.

Setting S_3 = 11.85 inches puts arms 3 and 4 in separate sectors.

The calculated k_{eff} for this system, using the diameters previously assigned, is $k_{eff} = 0.852 \pm 0.018$.

Example 3 (See Figure 5)

For this example, the column diameter is allowed to vary. Consider first the sector containing arm 1. Only one quadrant is used, so $d_1 = d_2 = 7.25$ inches.

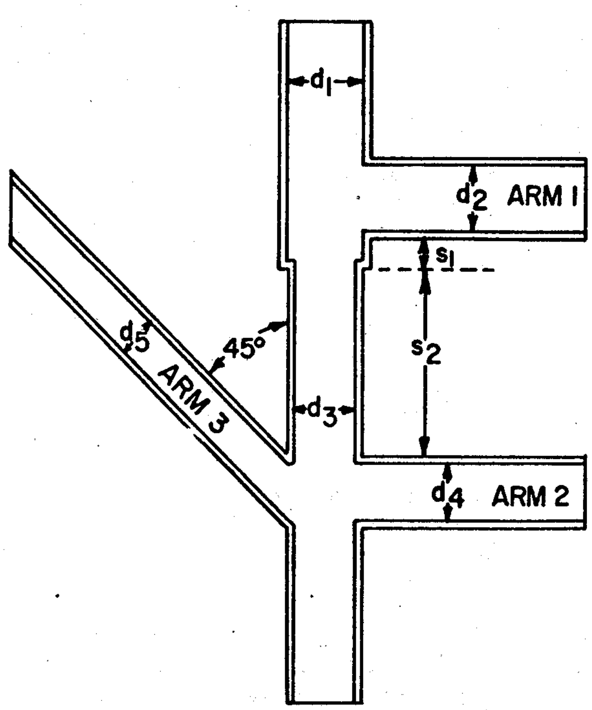

Fig. 5. Pipe system with central column of variable diameter. See Example 3 for calculation of safe dimensions.

Next, the sector containing arms 2 and 3 uses two quadrants, and the maximum column diameter is d_3 = 7.0 inches. For the arms, d_4 = 6.15 inches and d_5 = 5.17 inches (by the same calculations used for arms 1 and 2 of Example 2).

The distance S_2 must be chosen so that the 7.25-inch part of the column cannot be placed in the same sector with arms 2 and 3. This is prevented by setting S = 18 inches. There is no restriction on S_1, since the choice of S_2 is sufficient to put arm 1 in a separate sector from the one containing arms 2 and 3.

To check the conservatism of the GAI model, two 05R calculations were made for this example. With all diameters and spacings as calculated, and with $S_1 \approx 0.2$ inches, $k_{eff} = 0.833 \pm 0.017$. For $S_1 \approx 18$ inches, $k_{eff} = 0.821 \pm 0.016$.

Comparison of GEC and GAI Models

A different model for evaluating the safety of pipe intersections for fissile solution was described in RFP-1499.[29] This model, called the Generalized Equivalent Cylinder (GEC) model, is based on the idea of replacing an intersection by an equivalent cylinder, whose height and diameter are calculated from the parameters of the intersection. The intersection is deemed safe if the equivalent cylinder is subcritical.

When applied to uranyl nitrate solution, the GAI model generally allows much larger diameters than the GEC model. Exceptions may occur in the case of a quadrant containing several arms, since the GAI model makes the overconservative rule that the total allowable area is to be divided among the various arms (see Example 1, results for arms 1-6).

Suggestions for Use of the Model

The derivation of the GAI model required only properties common to all fissile solutions, such as the reflector savings correction or the fact that k_{eff} is decreased by replacing one pipe by several smaller ones with the same total area of intersection. Hence, the concept of the GAI model can be applied to other fissile solutions (e.g., plutonium, ^{233}U, or low-enrichment uranium) if calculations or experiments are performed to provide the appropriate numerical values for column diameter and intersection area as given in Table II for uranyl nitrate. The rules of the model are exactly as given here.

Recent French experiments [17] indicate that the GAI model, using the data given in Table II for uranyl nitrate, would be even more conservative when applied to certain bare plutonium solution systems. In particular, plutonium nitrate solution (3.13% ^{240}Pu, acidity about 2N, concentration > 82 g/liter of ^{239}Pu) is found to be less reactive than uranyl nitrate (90% ^{235}U, acidity about 2N) for the same concentration of the fissile isotope.

A second possible variation of the GAI model concerns the particular column diameters and corresponding intersection areas given in Table II. If, for example, one did not need column diameters as large as those given in Table II but needed instead larger intersection areas, one could make such modifications if appropriate calculations or experiments were performed to support these changes, but the basic assumptions of the GAI model would still apply.

The referenced article[26] suggests that, whenever possible, proposed pipe systems for fissile solution be evaluated using both the GEC[29] and the GAI models. Since both models are adequately conservative, one can choose the model that gives the better result in each particular case.

c. Other Calculational Methods

Monte Carlo calculational codes are now used extensively for calculating safe neutron interaction between arrays of fissile subcritical units or piping intersections as illustrated in the previous section. For unique piping problems that cannot be easily estimated with the GAI model or for less conversative results, the GEM4, MONK, KENO, or other suitable Monte Carlo codes may be used.